Latest Advances in the Microwave Observatory of Subcanopy and Subsurface (MOSS) Project

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***Abstract* – Measurements of deep and subcanopy soil moisture are critical in understanding the global water and energy cycle, as well as the interactions of the carbon and water cycles, but are presently not available on a synoptic basis. In this paper, a low-frequency UHF/VHF radar mission concept is presented and technology challenges to implement it are discussed. This mission concept is currently being studied under a NASA/ESTO instrument incubator program (IIP) project. The progress of several aspects of the project is presented.**

I. INTRODUCTION

Microwave Observatory of Subcanopy and Subsurface (MOSS) is a synthetic-aperture radar (SAR) Earth-orbiting system under conceptual development as part of the NASA Earth Science Technology Office Instrument Incubator Program (IIP) for global observations of soil moisture under substantial vegetation canopies and at depths of down to several meters [1]. It consists of a SAR operating simultaneously at two low frequencies, one in the UHF and the other in the VHF range. There are several challenges for implementing such a system, which are being studied and mitigation strategies being developed. These include the design of a large aperture antenna and prototyping of its feed system, development of a prototype science data set, development of soil moisture estimation algorithms, frequency interference analyses, correction of ionospheric effects, and evaluation of the impacts of MOSS products on global water and energy balance and Carbon cycle studies.

The required repeat observation period of 7-10 days imposes a requirement on the instrument's swath width and hence the antenna size. Specifically, both frequencies require an antenna length of at least 30m, while each requires a different antenna width (wider at VHF, proportional to wavelength). Using conventional phased array technologies, the two antennas, even with a shared-aperture architecture, would have a mass in excess of 4000 kg, rendering the mission unfeasible. The concept proposed by MOSS is to synthesize the two different antenna widths on a single parabolic mesh reflector of 30-m diameter by subilluminating the reflector surface with a dual-frequency stacked patch microstrip array feed. The resulting total antenna system mass is one order of magnitude lower than the conventional approach while carrying significantly lower risk than other antenna concepts such as inflatables. MOSS is prototyping this antenna feed system to show the feasibility of the overall concept.

A tower-mounted mobile radar system has been developed to produce several prototype science data sets for MOSS. The tower radar operates at the same UHF and VHF bands as MOSS, with the addition of an L-band capability to simulate other possible future L-band radars in space. During the next two years, this radar will be operated at several diverse locations that encompass arid/semiarid, temperate, and boreal climates with various soil types and vegetation covers. The soil moisture products derived from this system will be used to show the anticipated range and quality of MOSS products and their utility in global climate studies. Water and energy balance, as well as Carbon cycle, modeling is an integral part of this project and is being carried out to assess the impact of prospective MOSS data products. Other important aspects of this project are the correction for ionospheric effects (manifested in signal attenuation, polarization rotation, and reduction of coherence within the synthetic aperture) and analysis of frequency interference from and to other systems operating in the same frequencies.

II. SAR SYSTEM DESIGN

A preliminary design for a radar system capable of simultaneously meeting all of the measurement requirements mentioned above has been completed [2]. The system parameters are summarized in Table 1. The pulse repetition frequency (PRF) was maximized to lower the azimuth ambiguities to a reasonable level but is still low enough to achieve a swath width that fulfills the revisit time requirements. A long (140us) pulse length is used for both systems enabling a relatively low transmit power of 2kW. To assess the performance of the proposed system, an echo simulator was written that incorporates a Bragg rough-surface soil backscattering model. Also incorporated are modeled E- and H-plane antenna patterns at both frequencies that take into account the effects of blockage and enable us to calculate the azimuth and range ambiguities.

Table 1. Summary of SAR system design parameters

Parameter	UHF	VHF
Altitude	1313 km	1313 km
Swath Width	346 km	346 km
Antenna Width	2.8m	11m
Antenna Length	30m	30m
Center Frequency	435 MHz	137 MHz
Bandwidth	1 MHz	1 MHz
No.Looks/1km (min.)	54	40
Peak Power (1 channel)	2kW	2 kW
Pulse Length	140usec	140usec
Duty Cycle (2 channel)	13%	13%
Avg. Power (2 channel)	255W	255W
PRF (1 channel)	455Hz	455Hz
Processing Bandwidth	137Hz	182Hz
Data Rate (dual channel)	1.7Mbps	1.7Mbps
Incidence Angle Range	16-32	16-32
Azimuth Ambiguities	-18dB	-20dB

Figure 1 shows some results from these simulations for P-band (UHF). In this figure the upper panel shows the predicted H-polarized performance and the lower panel shows the predicted V-polarized performance. Note that in these figures the green line is simply a reference that indicates the timing of the transmit pulses relative to the echoes but is not adjusted in any way to match the power levels on the graph. Also, the range-ambiguity levels are not plotted since the relative levels are very low (<-60 dB).

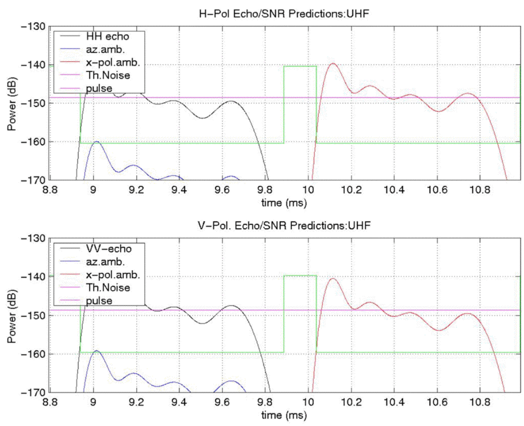

Figure 1. Sample simulations of SAR echoes.

III. ANTENNA DESIGN

The SAR system design for achieving the required wide swath indicated that the antenna length at both frequencies has to be at least 30m, while the width has to be 11m at VHF and 2.8m at UHF. Such an antenna, if implemented with state-of-the-art array technology, would have a mass of about 4000 kg, resulting in an unfeasible mission. Our antenna design synthesizes the same size apertures by subilluminating a 30-m mesh reflector symmetrically fed with a dual-stacked patch array. The resulting mass of the reflector, feed array, and support structures is estimated to be less than 500 kg. Figure 2 shows the array design and calculated radiation patterns, which are incident on the reflector [3]. Each of the UHF and VHF arrays will have honeycomb substrates with dielectric constant very close to that of air. A microstrip power-dividing network has been designed to deliver power to patches on each layer. Each patch will be fed from two locations corresponding to vertical and horizontal polarizations. A preprototype of the feed element is currently under construction. Upon successful testing, the element prototype will be built and tested, following by the fully populated array.

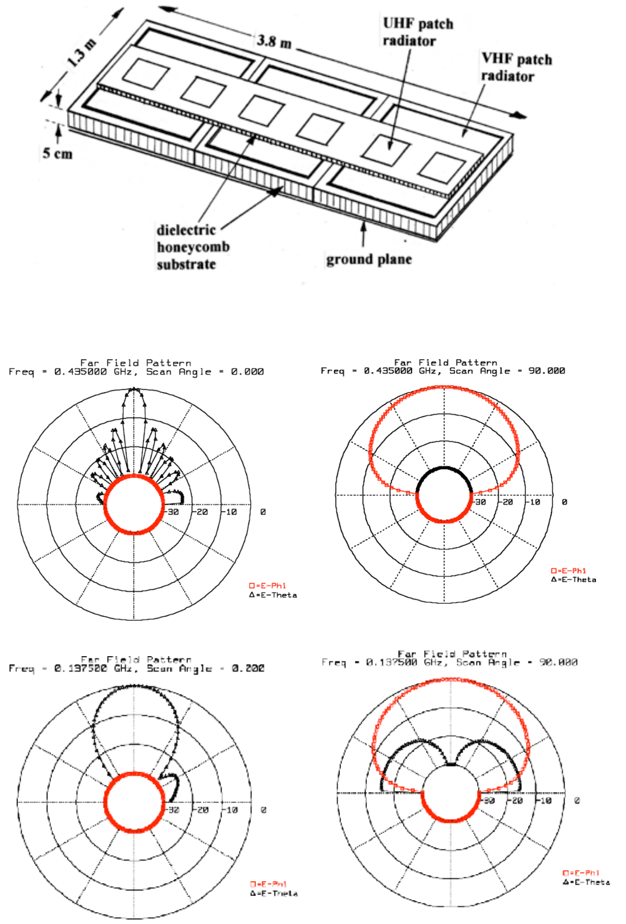

Figure 2. Top: schematic of dual-stacked patch UHF/VHF array. Middle: 6-element UHF array sample principal plane patterns at H-pol. Bottom: 3-element VHF array sample principal plane patterns at H-pol.

Figure 3 shows the schematic of the mesh reflector (courtesy TRW-Astro) and the calculated currents on the 30-m reflector generated by the dual-stacked patch feed of Figure 2, confirming the required effective aperture has been achieved. For additional verification of the calculations and testing the concepts, the dual-frequency feed element has been built and tested at the scaled frequencies of L-band and S-band, roughly a factor of 10 higher than the actual frequencies (Figure 4). Note that a novel feeding configuration is being evaluated for this higher-frequency version of the design, which uses thin coaxial lines to deliver power to each patch as opposed to a stripline [4]. The array and the power-dividing network for feeding the coax lines are currently under development. Once complete, the array performance is planned for testing at the UCLA spherical near-range chamber. Using an existing 3.65m reflector antenna, the full-up feed+reflector antenna system performance is planned for testing as well.

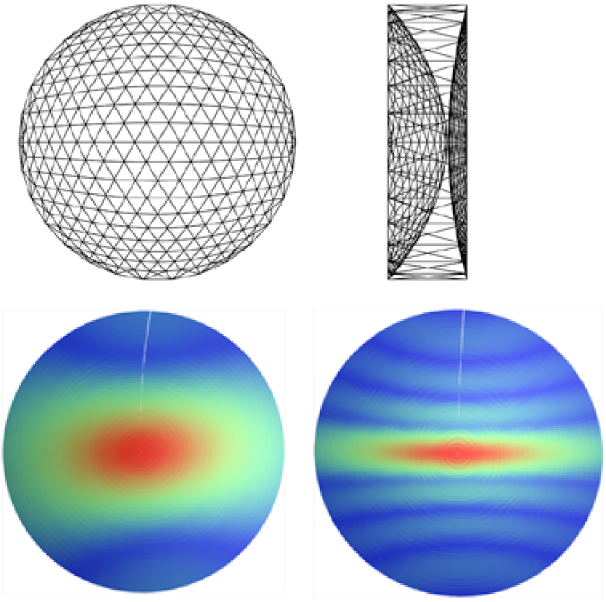

Figure 3a. Top: front and side view of the Astro-mesh reflector antenna aperture schematic (Courtesy TRW-Astro). Bottom: synthesized currents on the reflector, generated by the dual-frequency feed array in Figure 2.

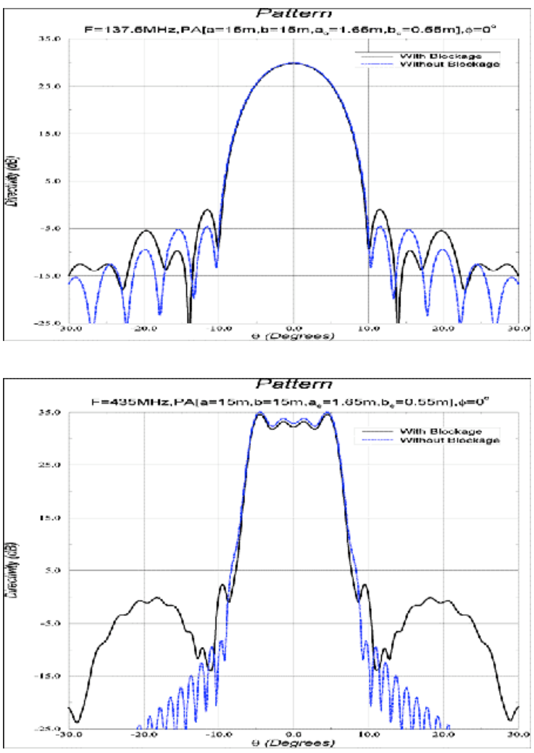

Figure 3b. Theoretical calculations of the resulting E-plane (cross-track) patterns for VHF (top) and UHF (bottom). The blue traces are the patterns without taking the feed array blockage into account, whereas the black traces include blockage effects.

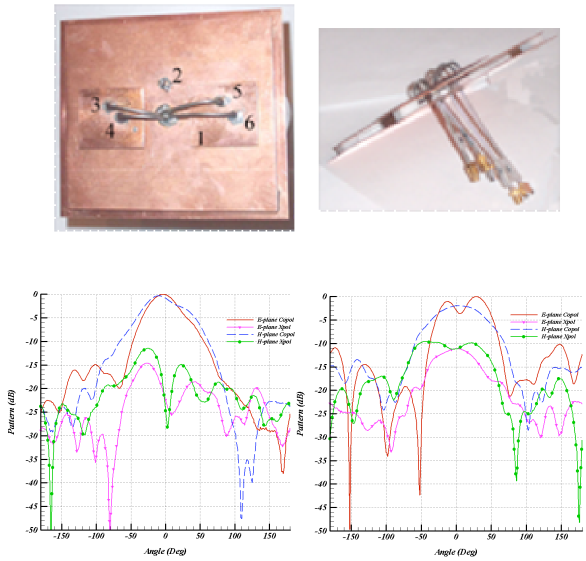

Figure 4. Top: L/S band scaled frequency element of the dual-stacked patch feed array, using a novel co-ax feed method. Bottom: measured radiation patterns at ports 3 and 4.

IV. TOWER RADAR AND FIELD EXPERIMENTS

To demonstrate the deep and subcanopy soil moisture products from the proposed UHF and VHF SAR instrument, we have developed a tower-mounted radar (Figure 5). This system is a pulsed polarimetric radar, and uses a log-periodic antenna (LPA) on both transmit and receive. A fast T/R switch is used to change the operating mode of the antenna between pulses. The radar operates at VHF, UHF, and L-band. The LPA is a dual-polarized wide-band antenna covering the frequency range of 80-1200 MHz, with return loss of no worse than 10dB across the band. The antenna beamwidth is several tens of degrees wide in all principal planes, requiring a beam focusing scheme to allow proper correspondence of the data to scattering target locations. Our beam-focusing method consists of synthesizing a large effective aperture by moving the antenna (mounted on the tower) vertically and horizontally such that the focused beam resolution cell is about 10m by 10m on the ground. The size of the synthetic aperture and sample spacing scale with wavelength. The antenna boresight is adjustable. The look angle of the focused beam can be controlled during post-processing, and is ideally in the 17-30 degree range to simulate the spaceborne system design.

To insure absolute amplitude calibration, 2.4m trihedral corner reflectors are used, whose theoretical scattering cross section is known. An active target, e.g., another antenna fed by the same signal generator as the radar, will be used for proper phase calibration as the radar antenna location is varied for aperture synthesis.

Since the transmit signal is switched to allow dual (T and R) operation of the antenna, the transmitted signal has a finite bandwidth determined by the switch transient characteristics. In our case, the effective bandwidth is about 30 MHz. We take advantage of this bandwidth to multilook in the frequency domain.

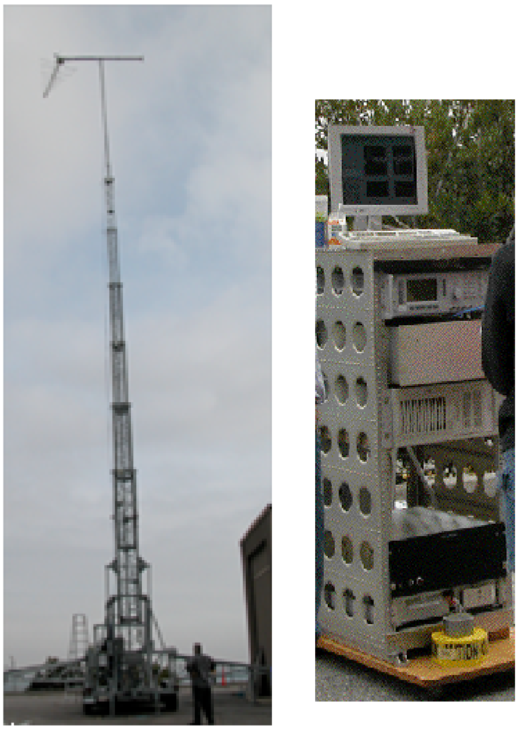

Figure 5. Left: Tower radar during full-up system testing. At full extension, the tower is about 45m high. The antenna pointing can be adjusted full range as needed. The tower telescopes up and down, and can be towed horizontally for 2D coherent aperture synthesis. Right: tower radar RF/Digital equipment set, rack-mounted.

The beam-focusing processor architecture is shown in Figure 6, and addresses a number of challenges for the tower radar. These include wide bandwidth focusing, real-time operation and debugging, calibration, and RFI removal [5].

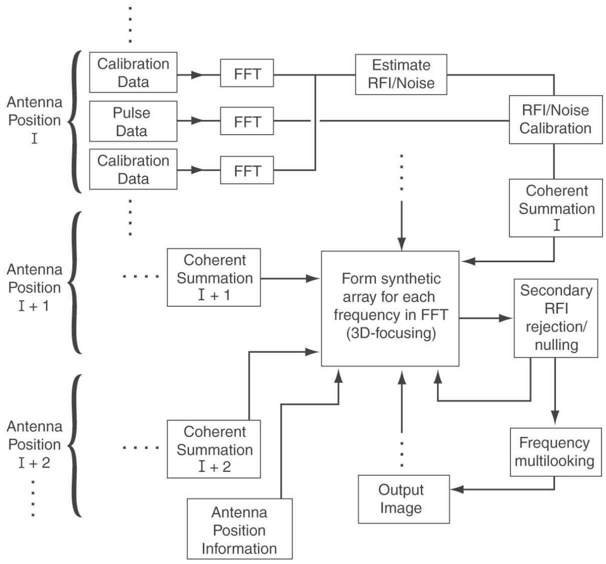

Figure 6. Tower radar processor architecture.

To characterize the effect of the tower mast on the LPA radiation pattern, a wire-mesh simulation model was used and the pattern of the LPA in the presence of mast calculated. Figure 7 shows the results for the VHF frequency, which is the worst-case scenario. Even in this case, the effect on the radiation pattern in very small. At UHF and L-band, the effect is even smaller, improving as a function of increasing frequency as the mast moves further in the far field of the antenna.

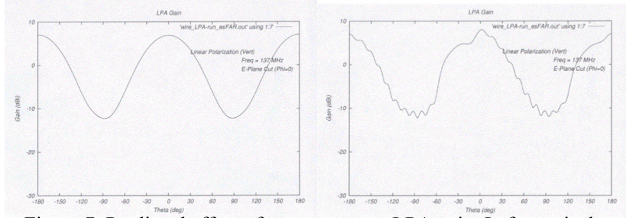

Figure 7. Predicted effect of tower mast on LPA gain. Left: vertical polarization E-plane cut for VHF without the mast. Right: vertical polarization E-plane cut for VHF in the presence of the mast.

A new generation of soil moisture estimation algorithms is being developed, which will be validated using the tower radar data. Here, the effects of soil penetration are being modeled and integrated into our previously developed forward and inverse scattering models for vegetation and soil characteristics. The soil is being modeled as a multilayered rough surface with various inclusions such as rocks (Figure 8). A numerical scattering solution (FDTD) for this soil model is being embedded in our existing forest scattering model, replacing the simple single-interface rough surface [6]. The inversion algorithm will take advantage of the multiple low frequencies available to calculate soil moisture in two soil column depths. Field experiments are scheduled for this summer and available results will be presented.

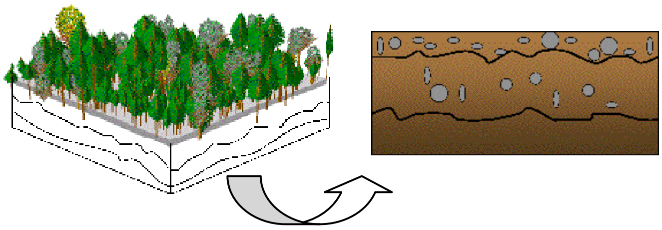

Figure 8. Vegetation and layered soil model used in development of the new generation soil moisture estimation algorithms.

The field locations cover a variety of vegetation and soil moisture conditions. They include an arid/semiarid site in the Lucky Hills/Walnut Gulch watershed in Arizona, a prairie grassland in Kansas, a grassland in Oregon, a shrubland in Oregon, a dense forest site in Oregon, and a boreal forest site in Manitoba, Canada. Soil moisture probes have been installed at these sites to maximum depths ranging from 30 cm to 200 cm. Some sample field locations are shown in Figure 9.

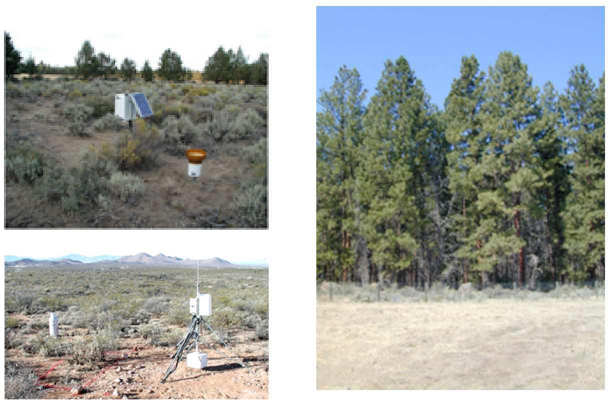

Figure 9. Top left, Oregon grass site; right, Oregon forest site; bottom left, Arizona site.

V. MESH REFLECTOR AND SPACECRAFT DESIGN

The advent of light mesh-type reflector surfaces has made it possible to launch and deploy large antennas in space at a much more reasonable cost than the significantly heavier antennas of the same size. An example of such a surface is the Astro-mesh by TRW/Astro (now Northrop Grumman) [7]. To study the mechanical and spacecraft design issues for MOSS, TRW/Astro has been performing detailed analyses related to the packaging, launch, deployment, and operations of the MOSS instrument.

Some highlights of the analyses results are:

- Although the desired effective aperture shape for MOSS is rectangular (30m by 11m at VHF and 30m by 2.8m at UHF), synthesizing this aperture on a parabolic mesh reflector is significantly preferred to a cylindrical mesh aperture from mass, packaging, and risk points of view. This confirms the appropriateness of our original concept.
- An F/D of 0.45, as selected to achieve science requirements for swath width, results in a package size in the optimum range. The package size is approximately 6.6 m long and 1m in diameter.
- The 30m antenna is not deemed to pose a major risk item for the mission. The technology has been demonstrated, e.g., on the 12m Thuraya antenna.
- The launch vehicle will be at least a Delta-III class.
- Two spacecraft options have been considered, each with its own advantages. Preliminary candidate deployment mechanisms for each case have been studied. In both cases, placing the spacecraft within the non-illuminated antenna aperture provides the shortest mast length for the deployed antenna and feed. A possible scenario is depicted in Figure 10.
- The propulsion, electrical, and attitude control subsystems do not have stringent requirements, and can be accommodated with existing technology. The on-orbit delta-V requirements for the MOSS mission can be accommodated with a simplified version of a baseline dual-mode, pressure regulated, bi-prop propulsion subsystem The 1313km 6am/6pm orbit has no eclipse, and hence batteries are only needed during launch and prior to solar panel deployment. The range of pointing requirements under consideration for the MOSS mission (1.0 deg required, 0.5 or 0.25 deg desired) can all be supported by a simple earth-sensor and sun-sensor attitude reference system.
- The low data rate of the MOSS instrument allows a rather low demand on the solid state recorder and the downlink systems.
- The mass of the reflector, boom, all mechanisms, and the dual-frequency feed is estimated to be less than 500kg.

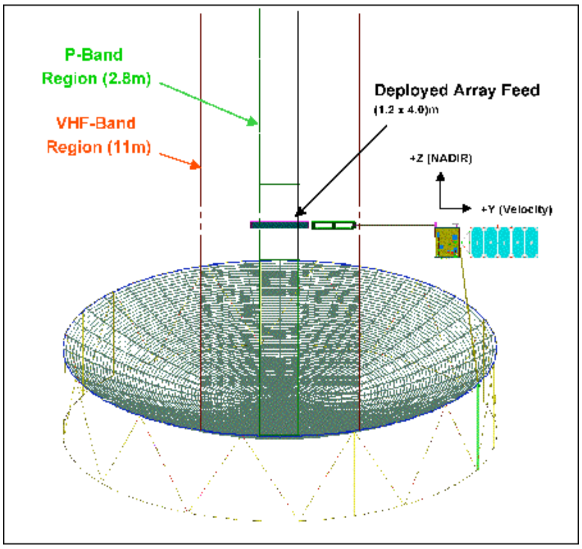

Figure 10. Possible deployed configuration of the 30-m mesh reflector. Spacecraft bus is in the "quiet" zone of the antenna to minimize the feed boom length.

VI. SUMMARY

The MOSS project is studying various design, technology, and scientific challenges for implementation of a UHF/VHF polarimetric SAR mission for global observations of deep and undercanopy soil moisture. Latest progress on all aspects are given in this paper. In addition to the topics noted in previous sections of this paper, ionospheric effects and impact on the study of global water and energy cycle will also be discussed at the presentation.

ACKNOWLEDGEMENTS

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